SUBJECT: Lunar Surface Models for Apollo
Case 320

DATE: April 24, 1967

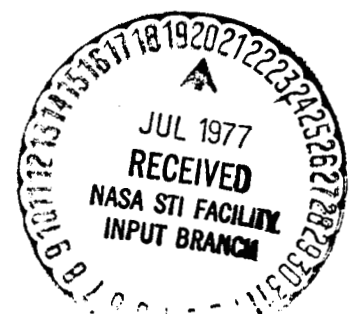**FROM:** W. W. Ennis
F. Heap

ABSTRACT

Analysis from three different viewpoints is used to
develop on a logical basis three models of the lunar surface
for use in the Apollo program. The first, a "Lunar Surface
Model for Surface Interaction", represents a worst case for
touchdown. It is in effect the model from which was derived
the structural specification to which the LM was designed.
The second, a "Lunar Surface Model for Landing Approach Oper-
ations", represents a worst case for finding and reaching an
acceptable spot to land on after the crew assumes the function
of redesignating the touchdown point; it is in effect a model
from which may be derived a specification for the operational
capability of the LM. Both models are compatible with current
LM characteristics and capabilities. These models are developed
in a suitable format for inclusion in the "Natural Environment
and Physical Standards for the Apollo Program" (NEPSAP), and
can readily be revised when necessary to reflect changes in
planned use of the LM or in available information about the
lunar surface. It is recommended that they be incorporated
into the NEPSAP.

The third model, a "Lunar Surface Model for Landing
Site Evaluation", is derived from the first two in such a manner
as to allow the planner to back off from the worst-case demands
upon the LM and crew capabilities and specify as hospitable or
"easy" a surface as is desired. This model is suitable for
inclusion in an Apollo Program Site Selection Criteria document.
It is recommended that it form the basis for preparation of
such a document by NASA Headquarters or MSC.

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MEMORANDUM FOR FILE

INTRODUCTION

This discussion presents a logical development leading to models of the lunar surface suitable for inclusion in the "Natural Environment and Physical Standards for the Apollo Program" (NEPSAP) and other program control documents. The surface characteristics to be described and the uses envisioned for the models fall more or less naturally into three classes; three models are therefore developed.

The first describes the properties of the surface that determine its mechanical interaction with the landing vehicle. The model presented here essentially reproduces the specification surface to which the Apollo Lunar Module structure has been designed and built; it thus represents, in terms of values assigned to appropriate parameters, a worst-acceptable surface for that vehicle.

The second model describes the worst-acceptable distribution of acceptable surface (as characterized in the first model) in the vicinity where landing is desired. This description is provided in terms of the capability of the Lunar Module and crew to fly to a landing point, as limited by uncertainties in guidance and control, by visibility of surface features, and by propellant quantity. Current LM guidance capability, operational concepts, and descent and landing strategy are assumed in formulating a simple match of the surface to the capability.

The third model is derived from the first two, with the surface characteristics that were developed in the structural and operational models here rearranged somewhat into separate measurable quantities. The limiting numerical values of these for a given mission may then be filled in in advance, to specify the worst surface it is desired to attempt to cope with on that particular flight. Available data on different parts of the lunar surface may then be compared to the criteria provided in the model in order to select a Landing Site that meets the specification.

Conclusions and Recommendations

        Three closely related descriptions of a lunar surface
have been developed, each with a different point of view and
purpose. In the development, a number of assumptions were found
to be necessary concerning relationships and correlations of
some observable surface characteristics. The numerical values
associated with these assumptions may later prove to be in error
but this does not invalidate the nature or the appropriateness
of the assumptions. Hence, the acquisition of additional data
on the lunar surface will allow adjustment and updating of the
models but should not require significant change to their struc-
ture. Should radically different LM descent strategy or touch-
down techniques be adopted the models would probably have to be
modified, but the basic approach of developing the models as
limiting or worst cases in terms of the structural and operational
capabilities of the LM appears to be valid and necessary. The
models appear, then, to be general and durable. They also are
believed to meet an immediate program need. It is therefore
recommended that the first and second models (Enclosure (1)) be
incorporated into the NEPSAP. They are numbered to replace the
existing sections therein. It is recommended that the third
model (Enclosure (2)) be used as the appropriate section in a
Site Selection Criteria document for the Apollo Program.

        Some further comments and recommendations are appro-
priate with respect to the assumptions, and the lack of informa-
tion characterizing them, discussed above. It seems incontro-
vertible that the criteria to be used for selection and rejection
of landing sites for Apollo must be stated in terms of surface
characteristics that can be measured by unmanned probes. It seems
highly desirable that such criteria reflect in a simple manner
the constraints imposed upon the landing vehicle by its structural
and mechanical limitations, and by the willingness of planners
and flight crews on a given mission to tax the capabilities of
the vehicle and flight crew within those limitations. While this
memorandum develops structural and operational limiting models
of the lunar surface and from them a site-selection model that
has these desirable properties, there appear to be three general
areas of observation and measurement in which improved data are
needed.

        The first concerns the means of making the comparison
mentioned in the Introduction between the criterion and the data
in the site evaluation process. When there is adequate informa-
tion of sufficiently high resolution this comparison can be a
simple point-to-point analogue matter, but when the reconnaissance
photography available on a desired site cannot show obstacles of
the smallest size recognized in the model a problem arises. Much
work has already been done on the development of statistical mod-
els of various types of lunar terrain in terms of probability
distributions of the sizes of features (craters), and the gradual

appearance of data of higher resolution has shown that these
distributions can with fair validity be extrapolated to smaller
sizes than are included in the data. A transformation is needed
between distributions of this sort and the maximum-/minimum-
distance characterization of the surface developed in this
Memorandum. The authors recommend that some analytical studies
be carried out to establish this correspondence and provide a
formalism giving a reasonable degree of confidence in site
selection from data whose resolution is, as is frequently the
case, "not quite high enough".

The second region of uncertainty and assumption con-
cerns the relative visibility of Good Regions and Hazards and
of Touchdown Spots and Hazards (see the discussion under Devel-
opment of the Models for definitions of these terms). Most of
the work done to date on visibility seems to have been directed
either toward construction of gross photometric functions or
toward estimating visibility (i.e., contrast) of individual
features under various lighting and viewing geometries. A
matter of immediate concern, however, is the flight crews' abil-
ity to recognize good or bad terrain at the point to which the
LM is guiding itself, from the Hi Gate and Lo Gate points in
the descent. This probably can only be evaluated properly by
the human eyeball in situ; the next best thing is photography
planned for the purpose, and Lunar Orbiter looks like the current
experimental program most capable of providing the needed
information.

The third area of concern is that of the correlation
of photographic data with surface mechanical properties. While
it probably already is justifiable, as is suggested in the later
discussion, to assume that the moon's surface is actually suffi-
ciently firm on any spot that looks sufficiently firm, there
should be more information and more explicit information in
corroboration. High resolution Lunar Orbiter photography on
landed Surveyors and Luniks is the medium that appears most fea-
sible at present. It is recommended that a significant portion
of the photographic mission of at least one Lunar Orbiter be
designed to provide information in the two areas just discussed,
and that all Orbiter and Surveyor photographs and data be so
analyzed as to maximize the amount available of such information.

It is shown in the discussion that problems of visi-
bility and avoidance of dangers in the landing area lead to
requirements on flight crew training. The degree to which en-
hancement of the crews' discrimination and redesignation capability
can mitigate demands for surfaces that are almost perfect, and

on which terrain features are easily discernible, is not known.
It is recommended that this tradeoff between flight crew require-
ments and landing site requirements be analyzed in cooperation
with the people responsible for planning and implementing flight
crew training at the Manned Spacecraft Center.

DEVELOPMENT OF THE MODELS

LUNAR SURFACE MODEL FOR SURFACE INTERACTION

The Touchdown Point

        The smallest element of the surface that is signifi-
cant as an entity is that occupied by a LM in normal landed
attitude on the surface. It is taken to be a circle of diameter
30 feet (9 meters), the diagonal of the LM foot pad array (5.8.1).*
We specify that the surface supports the LM without too much
penetration by the pads (5.8.1.2, 5.8.1.4, 5.8.1.5), that it
supports the LM at an acceptable inclination for surface opera-
tions and subsequent ascent (5.8.1.1), and that the surface
material does not project upward between the pads enough to dam-
age the LM (5.8.1.2). Since the LM cannot be constrained to
touch down with zero horizontal velocity it is necessary to bound
the magnitudes of the horizontal interaction forces, to prevent
sliding excessive distances and possibly to limit the structural
loading (5.8.1.3). We call the element so described a "Touch-
down Point" and locate it by the coordinates of its center.

LUNAR SURFACE MODEL FOR LANDING APPROACH OPERATIONS

The Touchdown Spot

        An isolated Touchdown Point is not big enough to land
on, for several reasons: the crew cannot control the LM precisely
enough to hit such a small element; the crew probably could not
see such a small element from the point at which they take over
manual control of the vehicle (Lo Gate); and the LM is likely to
slide on the surface before coming to rest. We therefore de-
scribe a larger element as the minimum on which we will try to

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        *The numbers in parentheses in this and subsequent paragraphs
    refer to the identically numbered items in the specimen
    models contained in the attached Enclosures (1) and (2).
    Enclosure (1) is numbered as a replacement section for the
    NEPSAP.

land, and require that every 9-meter circle within it be a Touchdown Point having the characteristics described above. About three times the diameter of the Touchdown Point is an appropriate size consistent with the results of simulation exercises that have been conducted to determine the precision with which the LM can be landed. We call this element a "Touchdown Spot" (5.8.2.3) and take it to be a circle 30 meters (100 feet) in diameter.

Distribution of Touchdown Spots; "Good Region"

In flying the LM down to the surface there comes a point where, if there is not an acceptable place to land within reach, the crew must abort the landing and return to orbit. The exact instant by which this decision must be made will vary with the mission; it is here taken conservatively and for convenience to be at Lo Gate. "Within reach" is assumed to mean both in the Crew Commander's field of view and within the horizontal distance capability of the LM from Lo Gate. The Commander's field of view is limited (by the window) to the region generally to the left of and not too far from the +Z axis of the LM. The normal horizontal translation of the LM from Lo Gate to touchdown is about 1200 feet (370 meters); it has capability for variation of about 300 meters in the downrange and crossrange directions. Uprange redesignation is rejected because the maneuver drops the landing point out of the field of view. Crossrange redesignation without a corresponding downrange component requires excessive roll angle, and is also eliminated. The region that remains within reach is essentially a quadrant 300 meters in radius lying between 10 o'clock and 1 o'clock relative to a point 370 meters dead ahead. If there is to be a landing, then, there must be a Touchdown Spot within this region relative to the point at which the LM comes to Lo Gate. A distribution of Touchdown Spots having this property with respect to every point, and with a minimum number of Touchdown Spots per unit area, is the artificially regular pattern in which the Touchdown Spots are equidistant (i.e., at the vertices of a close-packed array of equilateral triangles) and the centers are 250 meters apart. In such a distribution, with the Touchdown Spots 30 meters in diameter, the center of each triangle is about 125 meters from the nearest points of the Touchdown Spots at the triangle's vertices. 125 meters is thus the greatest distance from any point on this surface to a Touchdown Spot. This number, characteristic of this minimum-density distribution of Touchdown Spots, may then be applied as a criterion to any distribution. A surface on which no point lies farther than 125 meters from a Touchdown Spot meets or beats a requirement that there be a Touchdown Spot "within reach" (as defined above) in any specified direction from a point selected at random. In a landing area that meets such a requirement it will make no

difference where the LM comes to Lo Gate; a landing can always
be made. In the Lunar Surface Model for Landing Approach Opera-
tions a region where every point is within 125 meters of a Touch-
down Spot is called a "Good Region" (5.8.2.2).

Note that the exact distribution and density of Touch-
down Spots in this benevolent region is not specified: it can be
anything from a scattering of the minimum 30-meter circles to a
surface composed entirely of Touchdown Points. An intermediate
distribution often discussed and considered desirable is one where
the surface consists almost entirely of Touchdown Points but con-
tains a scattering of obstacles on which landing is not feasible.
Such obstacles can evidently be of any size, from single rocks
to rough areas of considerable extent. (The term "hazard" has
sometimes been applied to any rough areas or obstacles that would
interfere with landing; since that word is restricted in this
discussion to a particular well-defined size of obstruction, these
general bad areas will here be called simply "Rough Spots".) It
is seen immediately that the presence of a Rough Spot large enough
to contain a circle 250 meters in diameter destroys the benevolent
character of the region; if the LM reaches Lo Gate aimed at some
points in the interior of such a large Rough Spot, there is no
Touchdown Spot within reach. It is also apparent that the spacing
of the Rough Spots has to be such that the accessible areas between
them are big enough to see and land on; the smallest allowable
size of each such accessible area, if it is to be usable, is that
of the Touchdown Spot. Obstacles of negligible area (e.g., single
rocks) would reach a maximum allowable density in an artificial
regular hexagonal distribution pattern, with the separation between
adjacent rocks just 15 meters and a Touchdown Spot centered in
each hexagon of the pattern. In a distribution of this nature,
if some of the obstacles were to be so close together that the
clear areas between them, although containing Touchdown Points,
did not provide a Touchdown Spot, then the whole set of obstacles
involved would have to be treated as a single Rough Spot. The
models do not contain explicit mention of Rough Spots, since all
of the above inference concerning them follows directly from the
definition of Good Region.

It should be noted that the difference between a surface
that just meets the criterion and is Good Region and one that
just fails to meet the criterion is infinitesimal. This is true
regardless of the nature of the surface: whether it is smooth
with scattered rocks or rough with scattered smooth places.

Hazards

If a Good Region were large enough to get into on auto-
matic guidance alone (i.e., at least big enough to enclose the
guidance/navigation error boundary), the provision of visibility

at Hi Gate would be unnecessary; the Powered Descent could be
flown in a propellant-minimum mode all the way to Lo Gate. As
it is operationally unnecessary and may be unduly restrictive
to require that any very large area be composed entirely of Good
Region, we do not rule out the possibility of the presence, in
the vicinity of the desired landing point, of Rough Spots whose
inscribed circles would be greater in diameter than 250 meters.
The term "Hazard" is reserved for such areas in this model.
Since the LM may not be able to land if it comes to Lo Gate aimed
at some points in the interior of a Hazard, it is necessary that
these points be avoidable and highly desirable that the entire
Hazard be avoidable from some point before Lo Gate. The earliest
instant at which the crew can know that the LM is being guided
into a Hazard is Hi Gate, the point at which the LM is first
pitched down to afford the crew a look at the landing area. The
upper bound on size of an avoidable Hazard is provided, then, by
the avoidance (i.e., redesignation) capability of the LM at Hi
Gate. For generality and simplicity of the model this is taken
to be 1000 meters in any direction, although it is recognized
that the redesignation pattern is not symmetrical in the up/
downrange direction and that its size depends upon the altitude
of Hi Gate. For the model, then, the size of an avoidable
Hazard is bounded by the conditions that it contains points
farther than 125 meters from any Touchdown Spot but no points
farther than 1000 meters from a Touchdown Spot (5.8.2.4). Note
that a Hazard so defined is not necessarily round like a crater;
it may be a valley or a ridge of any length and not at all straight,
so long as it is 2000 meters or less in effective width.

Visibility and Spacing of Hazards

Just as the need for a spot suitable to touch down on
dictates a minimum degree of separation for Rough Spots, the
requirement that the Good Regions among Hazards be distinguish-
able as well as attainable dictates a constraint on the separa-
tion and the relative visibility of Hazards. Since, in our defi-
nition, Hazard is not explicitly different in appearance from
Good Region and the visual character of both may vary over a
wide range, no simple rule is likely to cover all cases accurately.
At one artificial extreme, where the Good Region consists of a
minimum-density scattering of minimal Touchdown Spots in a gen-
erally rough terrain, a place where a few adjacent smooth spots
are only 29 meters in diameter becomes a Hazard: it is unlikely
that such a thing would be recognizable even fairly near and
under favorable lighting conditions. (But note that the principal
artificiality here lies in the assumption of a sharp cutoff in
LM capability: in the example cited, the danger involved in at-
tempting to land on a 29-meter Sub-Touchdown Spot is actually
only slightly greater than that in landing on a 31-meter Super-
Touchdown Spot.) At another extreme, one can imagine a Good

Region having a maximum density of point obstacles on a surface that is otherwise composed entirely of Touchdown Points. Here a reduction in the spacing of the rocks around one of the clear areas to 14 meters instead of 15 makes a Rough Spot almost as big as a Touchdown Spot; a few of these together make a Hazard that is practically indistinguishable from the surrounding Good Region. Again the abrupt transition is artificial and arises from the simplifying assumption; the danger in landing in one of the undersized clear areas is only a little greater than that encountered in a legitimate Touchdown Spot. Toward still other extremes, however, the situation may be much more favorable (as well as much more realistic): a large very rough patch surrounded by flat smooth surface or a large flat patch surrounded by very rough surface should be conspicuous and dis- tinguishable from considerable distance under suitable lighting conditions. The greater the difference in visual character between the Good Regions and the Hazards, the easier it will be to distinguish between them and the farther away it will be possible to do so; also, in a roughly corresponding way, the farther away it will be necessary to be able to do so. According to our concept, two Hazards separated by Good Region that cannot be recognized as such must be regarded as a single Hazard. It is assumed for this model that a parcel of Good Region can be detected and recognized under the same viewing conditions as can a Hazard of the same size; hence a requirement is placed in the model that the minimum separation between two Hazards is about the same as the distance across the smaller of the two (5.8.2.4). This is arbitrary but represents a sort of minimum desirable condition; it points to the need for reexamining this question in connection with development of a site selection model, but is in itself not relevant to this model unless the model is to be used to test the crews' capability of recognition in addition to the LM's capability to maneuver. For simulation purposes, it may be desired to expand this model to incorporate features reflecting the lighting and photometric qualities of the lunar surface. In that case, further definition of the proc- ess of recognition of actual surface elements and the transposi- tion of them into acceptable/non-acceptable area classifications would be required. Better photographic coverage of the lunar surface is judged to be essential to this definition and to the development of useful and more exact rules for the spacing of Hazards and Good Regions. In any case the relative visibility of Good Regions and Hazards will ultimately depend upon the particular region being examined and the lighting conditions and LM altitude and range assumed.

Landing Site; Largest Allowable Hazard

If the crew were to make no landing point redesignation nor other interference, the probability that the LM guidance system alone would bring the LM to a landing at any given point on the lunar surface would be represented by a probability distribution around the Targeted Touchdown Point. This distribution is the result of guidance errors, navigation errors, mapping errors, errors in coordinate transformations, etc. The Targeted Touchdown Point itself would become a line segment 8 to 10 miles long instead of a fixed point if a range-free trajectory were to be adopted. A constant-probability boundary is likely to be shaped like an ellipse or a "stretched" ellipse; it is assumed here that the "3σ" or "Nσ" boundary is some reasonable smooth approximation to such a curve and enclosing the same total probability as with normal distributions.

It is assumed that all reasonably probable landing points lie within the 3σ navigation error boundary; the model calls the region thus bounded the Landing Site (5.8.2.1) and defines limits on the distribution of Good Regions and Hazards therein. Since at Hi Gate the LM may with reasonable probability be found to be aimed at any point in the Site, including the remotest interior point of any Hazard, to assure an equally reasonable probability of successful landing it is necessary that there be no Hazard larger than the "maximum" (2000 meters effective width) within this boundary (5.8.2.4).

Landing Approach Path

To complete the model, the surface should be prescribed in the entire region that can influence the vehicle's approach performance by way of the Landing Radar update of the guidance system. The region affecting the Landing Radar in approaching a landing point is essentially in the shape of a long triangle. The length of this triangle is determined by the distance from the landing point at which the radar becomes effective. The width of the triangle beneath each point of the trajectory corresponds to the width of the Landing Radar beam pattern on the surface; this width is approximately proportional to the altitude of the LM. Because of the uncertainty in the location of the LM's approach trajectory described above, the Approach Path for a particular mission includes all of the Landing Site plus an area swept out by translating the near edge of the Landing Site uprange a distance equal to that in which the Landing Radar is employed by the guidance system. The uprange translation is along all the possible LM approach azimuths for the mission.

The widening of the Landing Radar beam pattern on the surface when the LM is at higher altitudes produces an additional broadening in the uprange direction. The Landing Approach Path is usually described in terms of the distance over which the specification must apply, the mean slope, the local slope, and the maximum local altitude deviation as a function of the distance to the landing point. Only interim guidelines are available at present, pending adequate analyses of terrain-radar-guidance relationships. This section is therefore left open in the models (5.8.2.5 in Enclosure (1) and 6 in Enclosure (2)).

LUNAR SURFACE MODEL FOR LANDING SITE EVALUATION

Sections 5.8.1 and 5.8.2 of Enclosure (1), whose development is discussed above, set forth models that represent structural and operational limiting cases and are thus in a sense specifications on the LM. Sites that are much more favorable than these limiting cases will certainly be strongly desired for the first few lunar landings, with some relaxation of the requirements possibly following as experience is gained. It is desired, then, to develop a set of variable Landing Site Evaluation criteria that will allow specification of a Site of any degree of favorableness down to the worst possible (as specified in 5.8.1 and 5.8.2). It appears advantageous to attempt to describe the surface in terms of the same characteristics as were employed in the previous models, since these are the ones that are structurally and operationally significant to the LM. It also is necessary to describe the surface in terms of characteristics that can be measured by means not involving manned landings: Lunar Orbiters, Surveyors, perhaps manned orbital reconnaissance missions, etc. With a little rearrangement and restatement, the characteristics used to describe the limiting surfaces in the structural and operational models can be used in a Site Evaluation model as well. The variable nature required is provided by the possibility of the insertion of different numbers where it is desired that some characteristic be less threatening or less difficult to accommodate than in the worst-case model.

Touchdown Point

The structural model (5.8.1) defines, for the present LM design and currently planned landing velocities, a Touchdown Point that is the worst on which the LM can land. A landing surface that offers something better than this is needed, so we write modified criteria for the Touchdown Point (Enclosure (2) Section 1). The size of it is still the smallest element over

whose extent we need to specify the general surface character-
istics. This is again taken to be the circle circumscribing the
LM foot pad array, since this is the appropriate unit from which
to develop Touchdown Spot size and characteristics. The "effec-
tive slope" (5.8.1.1) and "effective protuberances" (5.8.1.2)
cannot be measured until after the LM lands, since they involve
LM dynamics and surface interaction; it is therefore not mean-
ingful to specify these characteristics in a site-selection
model. They are separated in this model: the effects of surface
irregularities are limited by the surface objects requirement (1.2);
the effects of foot pad penetration are taken care of in 1.4;
all that remains to be specified is a topographic slope (1.1).

       Since it is desired to limit the distance the LM will
slide, a minimum coefficient of friction for horizontal sliding
of LM foot pads is specified (1.3). It is also possible and
may be appropriate to specify an upper limit to the coefficient
of friction. While this may be allowed to be effectively infi-
nite as in the structural model, if operational constraints
should be relaxed so as to permit higher horizontal velocity
at touchdown it might be desired to limit the possible dynamic
stresses in the LM structure by placing some other limit on the
coefficient of friction. The specimen model offers a simple
upper limit statement (1.3); alternatives would be a no-limit
statement as in the structural model, or a statement that the
protuberances and depressions are of such size and distribution
that a sliding LM foot pad will <u>not</u> at any point seize, etc.
It appears that a homogeneity requirement may also at times
be appropriate: a discontinuous transition after touchdown from
a relatively slippery rock surface to the "seized" condition
for a foot pad might induce excessive stresses at higher hori-
zontal speeds.

       The requirements on bearing strength of the surface
(1.4) are stated in essentially the same form as the requirements
in the structural model, without any assumptions as to the com-
position or nature of the surface material. The increase in
favorableness required for a particular mission may be written
in by inserting the numbers desired for a less penetrable surface.
A homogeneity requirement might be placed on bearing strength
also, in order to reduce the dispersion in "effective slope".

Meaningfulness of Mechanical Criteria

       A word should here be said about these purely mechan-
ical properties of the surface materials: bearing strength
and surface friction. Detailed probe measurements of these
qualities are obviously going to be extremely scarce; it seems

probable that there will never be a complete advance sample from
any Landing Site to be used--at least until the advent of homing
guidance on pre-placed beacons. It is expected, however, that
surface strength and friction characteristics will correlate
reasonably well with surface appearance and will not change
abruptly from point to point. It is hoped that corroboration
of this expectation will be obtained from unmanned probes, al-
though the information already available that the lunar surface
is strong at several widely separated spots will probably allow
us to make the assumption that a place that looks firm is firm,
in the absence of any evidence to the contrary. The probable
reality remains that, however uncertain it is, the evaluation
of these surface characteristics for site-selection purposes
will in most cases be done by analysis of photographs. In any
case the LM maintains the capability to abort during and after
touchdown, so that even if the surface should prove to be treach-
erously yielding there will be a reasonably dependable avenue
to safety.

Touchdown Spot

        To continue with the rationale of the model, it is
recognized as before that an isolated Touchdown Point surrounded
by unacceptable surface is not a suitable place to land. A min-
imum acceptable area, The Touchdown Spot, in which any 9-meter
circle is a Touchdown Point, is specified (2). The Touchdown
Spot may be made any size desired, and for conservatism will
probably usually be larger than the size assumed in the opera-
tional model (5.8.2.3). The Touchdown Spot must not, however,
be specified to be any larger than is really needed. Current
reconnaissance photographs indicate that large unobstructed
smooth areas on the moon are rare, and it would be easy to write
landing site criteria so conservative that few or no sites
meeting the requirements could be found.

Good Region

        Good Region (3) is, as in the operational model (5.8.2.2),
a kind of favorable domain in which the LM can with sufficiently
high confidence reach a Touchdown Spot after coming to Lo Gate
aimed at any point in the region. It is defined in the same way
as in the operational model: in terms of the maximum distance to

a Touchdown Spot from any point in the region. If this maximum
distance is specified to be about half the redesignation capa-
bility of the LM at Lo Gate (see the paragraph Distribution of
Touchdown Spots in the discussion of the Lunar Surface Model for
Landing Approach Operations), the surface demanded is at least
as good as the minimally hospitable surface of the operational
model. If the maximum allowed distance is less than that number,
the Touchdown Spots must be closer together and therefore easier
both to see and to get to. If the maximum distance to Touchdown
Spot is about 15% of the radius of the Touchdown Spot or smaller,
the Touchdown Spots run together and the region becomes one that
is all Touchdown Points except for scattered Rough Spots. In
this case the maximum distance to Touchdown Spot is effectively
a maximum allowed radius for the Rough Spots; the minimum spacing
of the Rough Spots is still determined by the requirement that
each be surrounded by Touchdown Spots. The maximum density of
such obstacles is easily seen to be two per Touchdown Spot.
There does not seem to be any reason to demand a lower maximum
density of Rough Spots unless, perhaps, a completely automatic
landing or a no-visibility landing were to be contemplated.

Hazards

Hazards are defined in the operational model (5.8.2.4)
by the presence of points farther from the nearest Touchdown
Spot than the limiting maximum distance to Touchdown Spot in
Good Region (5.8.2.2). In the site-evaluation model that limiting
maximum distance to Touchdown Spot in Good Region may be reduced, in
order to reflect the desired degree of conservatism in the de-
mands that it is proposed to allow to be placed on the LM trans-
lation capability from Lo Gate. To reflect a corresponding
conservatism in the limitation on the possible demands for rede-
signation before Lo Gate, "Hazard" is defined as before as a
region containing points farther from a Touchdown Spot than the
maximum distance allowed in Good Region (4). This definition
takes in some possible intermediate regions where the maximum
distance to Touchdown Spot is less than the redesignation capa-
bility of the LM at Lo Gate and which are therefore not impossible
to land in; for simplicity and conservatism these are not distin-
guished in the model.

Landing Site

Since the shapes of the contours of equal probability
in the LM landing position error pattern are likely to vary from
mission to mission, the specification of the Landing Site shape
and size has been left in the form of a 3σ probability statement
in the specimen site-selection model (5). A larger number than

3 may be used if a higher confidence of being aimed into a
suitable landing area is desired. It will be preferable, in
writing a site-selection specification for an actual mission,
to define the Landing Site extent in geometric terms (such as
"a circle five miles in diameter") relative to the Targeted
Touchdown Point to be selected rather than in probabilistic
terms related to performance errors. Then the burden of inter-
preting hardware performance is not shifted to people whose
business is interpreting photographs. It appears also that
some reasonable fraction of the total Landing Site area should
be suitable for landing. Since Hazards by definition include
some area that is also by definition Good Region, this limit
is stated inversely, as a maximum fraction of the total area
that may be occupied by Hazards (5.1).

Largest Hazard

        It is necessary to place another limit on the unfavor-
able character of the site. While the size of the largest allow-
able Hazard will normally be dictated by the largest allowable
redesignation the LM may have to make, it is not necessary that
it be limited in this way. In some cases--to land near a spe-
cific point of great importance but in poor landing country,
for example--a significant probability might be accepted that
the LM would turn out at Hi Gate to be aimed into a Hazard of
such size that it could not redesignate to a Good Region. This
does not mean the acceptance of a higher probability of crew
loss--merely a higher probability of abort without landing. For
a general site-selection criterion, however, the maximum Hazard
size should be less than the redesignation capability at Hi Gate,
so that it should never be necessary to redesignate immediately
at Hi Gate. The smaller this maximum size of a Hazard in the
Landing Site is, the farther down the Final Approach path it will
remain possible to redesignate the landing point out of a bad
area.

        In the specimen model this is taken care of by giving
a size of circle inside which the largest Hazard must be able to
fit (5.2). It is a rather restrictive specification, in that it
does not permit the Hazard to be elongated as does the opera-
tional model (5.8.2.4). It would clearly be possible to be less
restrictive and limit one dimension less than the other, and so
allow the maximum Hazard to be elongated to any degree desired.
It might also in some special situations be desirable to limit
the extent of allowable Hazards in the direction of the LM
approach path or in the direction normal to that path--where it
was, for some reason, specifically desired to limit the possible

in-plane or cross-plane redesignation requirement. The Hazard size limit proposed in the specimen model is about half that encountered in the operational model.

Visibility and Spacing of Hazards

In the operational model an arbitrary and somewhat symbolic restriction was placed on the spacing between Hazards (5.8.2). For a Site Evaluation model, consideration must be given to the probability of being able to distinguish between Good Regions and Hazards at the distance at which action to avoid the latter must be taken. The previous discussion shows that the visual characters of Good Regions and Hazards may be essentially identical or may differ, attaining some unspecifiable degree of distinctiveness. If Good Region is specified as being sufficiently "good"--i.e., flat, smooth, clear, it is likely that very bad areas will be visually distinctive and relatively easy to recognize, and that the worse the bad areas are, the more distinctive they will be. On the other hand, a "barely bad" region--one that just misses being Good Region--though not readily distinguishable, will still be good for landing if for some reason it is not avoided. It is argued then that some size-separation-distinguishability relation should hold for very bad areas in an otherwise sufficiently good area, and that for bad areas only a little less good than the standard, it does not matter whether there is such a relation or not. A limitation like that of the operational model (5.8.2.4) on Hazard spacing will then permit recognition and avoidance action at an appropriate distance where the visual characters of the Good Regions and Hazards are markedly different and the taking of action is most critical, and the limitation on the allowable size of Hazards provides a controllable hedge against the uncertainty of our knowledge of the distance at which these distinctions can be made. By making both criteria sufficiently conservative, the probability of being unable to perform the required recognition and evaluation functions in time to redesignate out of a Hazard may be made as small as is desired.

A problem avoided above, but easy to imagine and difficult to exclude by specification, is that of a very bad area that is not visually distinguishable from a very good area. An example would be a flat field strewn with three-foot rocks at intervals of ten feet or so: this might well be indistinguishable from the flat field without the rocks if it was at the Targeted Touchdown Point and viewed from Hi Gate. There appear to be two effective protections against the dangers arising from the possible presence of such areas in or adjoining Good Region. The

first is the evaluation of visibility and conspicuousness of features that should be a subsequent part of the examination of sites that meet the geometric screening criteria of Touchdown Spot distribution, Hazard distribution, etc. The safest and simplest rule would be not to accept any site in which this kind of ambiguity could arise. The second protection lies in the training of flight crews. So far the site descriptions and criteria have been constructed as though the LM crew were to have no previous information whatever about the site: this is not probable, nor is it necessary or sensible to assume it. Just as some of the limitations and uncertainties of crew and vehicle capabilities create requirements that Landing Sites meet certain demands if they are to be acceptable (resulting in the writing of Site Evaluation criteria), our inability to prescribe or describe perfectly all aspects of any Landing Site places certain demands upon the preparation of the flight crews. If we have planned well and are fortunate, the processes of developing, evaluating, and matching these capabilities and requirements will converge compatibly. Whether it is feasible or not to eliminate all possible ambiguities or confusions of Good Regions and Hazards the crews ought, by a reasonable program of study of the reconnaissance photography and of exercises simulating landings on the site itself, to be able to attain a considerable degree of familiarity with the site. They should pretty well know where the confusing areas are and be prepared to take action if they find themselves heading toward one, even though they may not at first know exactly to which spot of which area the vehicle is trying to take them.

It appears from the above discussions that the requirements on Hazard spacing for redesignation purposes can pretty well be separated from those arising from problems of visibility. For the capability to redesignate out of a Hazard and into Good Region to exist, all that is required is that the Hazard have some suitably spaced Touchdown Spots around its periphery; for this Hazard and the presence of its surrounding Good Region to be recognized from Hi Gate (or any subsequent point) it is necessary that they have sufficient difference of visual character (as yet unspecifiable) as well as be of appropriate size. The assumption made for the operational model that areas of Good Region and Hazards of about equal size can be distinguished ought to be valid for some reasonable degree of difference of visual character between the two. We may protect against a lack or uncertainty in the visual distinction by limiting the allowable size of Hazards (as suggested above) and by making a more conservative restriction (than that in the operational model) on the separation of Hazards. The Hazard size limit proposed in the specimen model (5.3) is about half that

encountered in the operational model. It is again emphasized
that the sizes of these restrictions are arbitrary and based
upon assumptions. The relative visibility of isolated obsta-
cles, Rough Spots, Hazards, Touchdown Spots, and Good Regions
is a critical matter which ideally should be settled by low-
altitude high-resolution photographic and visual reconnaissance.
Surveyor photographs should be of assistance here, but the
Surveyor point of view is probably too low to give the best
evaluation of LM visibility from Hi Gate to Lo Gate. Orbiters,
on the other hand, though normally flying at much higher alti-
tude than the LM in these phases of the descent, should be able
with their high resolution cameras to develop sufficient infor-
mation to answer the question for any particular site and prob-
ably in general. To obtain such data it would be necessary
for the cameras to look out at near-horizontal elevation angles
and with the sun at systematically varying elevation angles
and azimuths relative to the line of sight; in effect, to
develop surface photometric functions on the scale of one meter
or less.

Location on the Moon where Landing is Desired

Finally for the Landing Site, the location of the
Site itself, or of the Targeted Touchdown Point, has to be
specified within some limits. The regions in which landings
are feasible will always be limited by trajectory and lighting
constraints. It is expected that the locations of the first
Landing Sites will be selected within these constraints on the
basis of minimizing difficulty and optimizing communications
and tracking, but that ultimately landings will begin to be
placed in the vicinity of points or features of particular
interest. Locations, then, are likely to be specified in terms
of geographic coordinate limits or relative to some surface
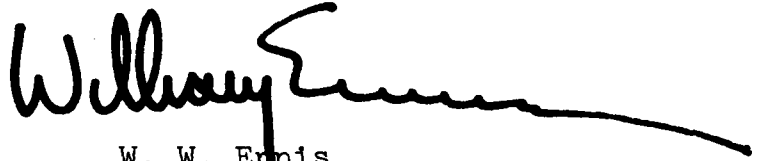feature of the moon (5.4).

Landing Approach Path

The description of the Landing Approach Path (6) is
left open, as explained in the discussion of the Lunar Surface
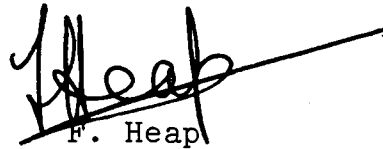Model for Landing Approach Operations.

Evaluation of Sites by Comparison of Experimental Data to Criteria

Given sufficiently detailed information about the lunar
surface--high resolution photography, bearing strength probes,
etc.--there would be no difficulty in selecting a Landing Site

using the criteria developed in this model. There would be high
confidence that the Site's contribution to the probability of
mission failure would be within the desired limits as well.
The hard problem arises when the pictorial information is limited
(the shortage of information on the mechanical properties of the
surface having already been discussed). A probable situation
will be that it is desired to land in a region where the only
information available is derived from pictures whose resolution
is such that obstacles of the smallest size of concern (and
possibly larger) cannot be seen. Determination whether the
surface satisfies the criteria relating to obstacles of a par-
ticular size then appears to be a two-step process. First is
extrapolation of the observable distribution of obstacles, in
whatever manner is possible and credible, down to the required
size. Second is the transformation of the parameters of the
extrapolated distribution, which must be in some statistical
form, into forms equivalent or comparable to the parameters of
the site-evaluation model. The latter are in a quasi-statistical
form involving maximum and minimum distances. It should not be
unduly difficult to develop a transformation of this nature,
and this correlation between a statistical distribution "model"
and a criterion model seems to be an important currently missing
link.

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F. Heap

2011-WWE
2013-FH   -vh

Attachments
Enclosure 1
Enclosure 2

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(see next page)

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ENCLOSURE (1)

5.8   Lunar Surface Model

        A statistical description of the lunar surface compa-
rable in accuracy to the descriptions provided of other elements
of the natural environment is not yet available. In the absence
of such a description two models are assumed, each representing
the limit or "worst case" with respect to a different critical
aspect of the overall system capability. The lunar surface
model for surface interaction described in 5.8.1 has character-
istics directly transformable to LM structural and mechanical
design characteristics. The lunar surface model for landing
approach operations described in 5.8.2 is defined in terms of
LM landing point redesignation capability and hence is related
to the LM fuel budget, guidance strategy, and control capability.

5.8.1   Lunar Surface Model for Surface Interaction

        This section defines the Touchdown Point, an element
of acceptable surface of such size as just to enclose a LM on
the surface in normal landing attitude. The Touchdown Point is
a circle of diameter 30 feet (9 meters) within which the surface
has the mechanical and topographic characteristics specified in
5.8.1.1 through 5.8.1.5. The position of a Touchdown Point is
specified by the coordinates of its center.

5.8.1.1 The "effective slope" does not exceed 12°. The effec-
         tive slope consists of the mean slope plus the combined
effects of protuberances, depressions, and footpad penetration.

5.8.1.2 The "effective protuberances" extend less than 24 inches
         (60 cm) above the mean surface. The effective protu-
berances result from the combined effects of objects on the sur-
face, variations of the surface itself, and footpad penetration.

5.8.1.3 The coefficient of friction for horizontal sliding of
         a LM footpad on the surface is greater than 0.4. In
addition, protuberances and depressions are of such size and
distribution that a sliding LM footpad may at any point seize
and be constrained from sliding farther.

5.8.1.4 The surface is composed of a combination of "structur-
         ally competent" and porous materials. The structurally
competent material is effectively infinitely strong and rigid;
i.e., it is not deformed by the LM. The porous material is a
cohesive or non-cohesive aggregate of unspecified thickness.
The combined material composing the surface is at least as strong
as the porous material alone, as described below.

5.8.1.5 The soil force resisting LM foot pad penetration in the
         porous material is greater than 5.5 psi (38,000 N/m^2)
initially and increases at a rate greater than 3.6 psi per foot
(81,000 N/m^2 per meter) of penetration.

5.8.2   Lunar Surface Model for Landing Approach Operations

         This section defines the Landing Site and the Landing
Approach Path.

5.8.2.1 A Landing Site is a region of the surface containing a
         Targeted Touchdown Point (TTP) and the entire 3σ landing
position navigation error boundary associated with that point.
A Landing Site is considered to consist of "Good Regions" and
"Hazards".

5.8.2.2 A Good Region is one where there is at least one Touch-
         down Spot within 125 meters (400 feet) of every point.
The magnitude of this distance reflects the landing point rede-
signation capability of the LM at Lo Gate: it is intended that
the LM can reach a Touchdown Spot from Lo Gate occurring over
any point in a Good Region without having to make radical maneu-
vers or changes of heading.

5.8.2.3 A Touchdown Spot is a circle of diameter 30 meters
         (100 feet) in which every 9-meter circle is a Touchdown
Point (as defined in 5.8.1). The size of the Touchdown Spot
reflects the LM's touchdown uncertainty from Lo Gate, and the
visibility and recognition requirements. It is intended that
the Touchdown Spot be visible and recognizable from a vehicle
at a distance of 670 meters and an altitude of 100 to 300 meters,
i.e., from Lo Gate, and that the LM be able to land on such a
spot in manual or automatic control when the center of the spot
is designated as the landing point from Lo Gate.

5.8.2.4 A Hazard is a region containing points farther than 125
         meters from a Touchdown Spot, but not containing points
farther than 1000 meters (3300 feet) from a Touchdown Spot.
This maximum Hazard size reflects the landing point redesignation
capability of the LM at Hi Gate: it is intended that the LM be
able to reach a Touchdown Spot from a Hi Gate point corresponding
to any navigation/guidance error within the 3σ limit.

5.8.1.5 The soil force resisting LM foot pad penetration in the porous material is greater than 5.5 psi ($38,000$ N/m^2) initially and increases at a rate greater than 3.6 psi per foot ($81,000$ N/m^2 per meter) of penetration.

5.8.2   Lunar Surface Model for Landing Approach Operations

This section defines the Landing Site and the Landing Approach Path.

5.8.2.1 A Landing Site is a region of the surface containing a Targeted Touchdown Point (TTP) and the entire 3σ landing position navigation error boundary associated with that point. A Landing Site is considered to consist of "Good Regions" and "Hazards".

5.8.2.2 A Good Region is one where there is at least one Touchdown Spot within 125 meters (400 feet) of every point. The magnitude of this distance reflects the landing point redesignation capability of the LM at Lo Gate: it is intended that the LM can reach a Touchdown Spot from Lo Gate occurring over any point in a Good Region without having to make radical maneuvers or changes of heading.

5.8.2.3 A Touchdown Spot is a circle of diameter 30 meters (100 feet) in which every 9-meter circle is a Touchdown Point (as defined in 5.8.1). The size of the Touchdown Spot reflects the LM's touchdown uncertainty from Lo Gate, and the visibility and recognition requirements. It is intended that the Touchdown Spot be visible and recognizable from a vehicle at a distance of 670 meters and an altitude of 100 to 300 meters, i.e., from Lo Gate, and that the LM be able to land on such a spot in manual or automatic control when the center of the spot is designated as the landing point from Lo Gate.

5.8.2.4 A Hazard is a region containing points farther than 125 meters from a Touchdown Spot, but not containing points farther than 1000 meters (3300 feet) from a Touchdown Spot. This maximum Hazard size reflects the landing point redesignation capability of the LM at Hi Gate: it is intended that the LM be able to reach a Touchdown Spot from a Hi Gate point corresponding to any navigation/guidance error within the 3σ limit.

The smallest Hazard within this definition is a circle 250 meters in diameter. The largest possible Hazard in an acceptable Landing Site is a strip 2000 meters wide extending clear across the Site. A Hazard may then be of any size or shape between these extremes.

Two Hazards may be no closer together than the average width of the smaller of the two, measured parallel to the minimum distance. It is intended that the Good Region between Hazards be recognizable under the same viewing conditions (distance, altitude, lighting) as the Hazards.

5.8.2.5 The <u>Landing</u> <u>Approach</u> <u>Path</u>

Left "open", pending adequate analysis of requirements.

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ENCLOSURE (2)

Lunar Surface Model for Landing Site Evaluation

This model specifies characteristics of the surface corresponding to the elements set forth in the structural and operational models in Sections 5.8.1 and 5.8.2 of the NEPSAP. The parameters are modified where necessary to correspond to characteristics of the surface (ascertainable or inferrable from experimental data) rather than to characteristics of the LM. The numerical values associated with the surface characteristics of a landing site considered acceptable for an actual manned mission will in general not be the same as those given in Sections 5.8.1 and 5.8.2 of the NEPSAP, since the latter represent worst usable cases. It is expected that the criteria chosen to guide the selection of possible landing sites for each mission will reflect the landing experience accumulated to date and the current conservatively estimated crew and hardware capabilities. For each mission the surface characteristic parameters will have special numerical values assigned, so as to describe a surface of the required quality in the range between the worst possible (as defined in Sections 5.8.1 and 5.8.2 of the NEPSAP) and the best possible. Criteria will thus be provided for selection of a site that will be at least as good as the standard that is considered to be not excessively difficult in view of the current 'state of the art'.

It is not intended that the various elements must be specified exactly in the forms indicated below: special requirements of particular missions may suggest alternative statements of some and the introduction or omission of others. Underscores in the material following indicate blanks, to be filled in for each mission; the entries inserted here are suggested ones for the first lunar landing mission.

1.   A Touchdown Point is a circle of diameter 9 meters
        within which the surface has mechanical and topographic
characteristics as set forth in 1.1 through 1.5:

1.1   The topographic slopes relative to the local horizontal
        are less than _5_ degrees.

1.2   There is no object on the surface of vertical dimension
        greater than _30_ cm.

1.3   The coefficient of friction for a sliding LM foot pad
        is greater than _0.4_ and less than _1.0_ .

1.4   The soil force resisting LM foot pad penetration is
          greater than 5.5 psi (38,000 N/m^2) initially and
increases at a rate greater than 3.6 psi per foot (81,000 N/m^2
per meter) of penetration.

2.   A Touchdown Spot is a circle of diameter 50 meters
          within which every 9-meter circle is a Touchdown Point
as defined in 1 above.

3.   For this mission, a region having no interior point
          farther than 100 meters from a Touchdown Spot is
characterized as Good Region.

4.   For this mission, a region having points farther than
          100 meters (same as maximum distance to Touchdown
Spot allowed in Good Region in 3 above) from a Touchdown Spot
is designated a Hazard.

5.   A Landing Site for this mission is a region enclosing
          the entire 3σ landing position navigation error boundary
relative to a possible Targeted Touchdown Point, and having within
it the surface characteristics set forth below:

5.1   Not more than 5% of the Landing Site area is Hazard;
          the remainder is Good Region.

5.2   No Hazard in the Landing Site may be of larger size
          than can be enclosed in a circle 1000 meters in
diameter.

5.3   The minimum distance between any two Hazards in the
          Site is twice the average dimension of the smaller
of the two, measured parallel to the minimum distance.

5.4   The Targeted Touchdown Point is in the desired or
          allowed position or region, specified geographically
or relative to some feature of the surface.

6.   The Landing Approach Path

          Left "open", pending adequate analysis of requirements.